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ULTRA HIGH ENERGY COSMIC RAYS: the theoretical challenge

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Abstract

The origin of the highest-energy cosmic rays remains a mystery. The lack of a high energy cutoff in the cosmic ray spectrum together with an apparently isotropic distribution of arrival directions have strongly constrained most models proposed for the generation of these particles. An overview of the present state of theoretical proposals is presented. Astrophysical accelerators as well as top-down scenarios are reviewed along with their most general signatures. The origin and nature of these ultra-high energy particles will be tested by future observations and may indicate as well as constrain physics beyond the standard model of particle physics.

Key words: cosmic rays, ultra-high energy, origin, acceleration,

1 Introduction

The detection of cosmic rays with energies above 10^{20} eV has triggered considerable interest on the origin and nature of these particles. As reviewed by Watson [1] in this volume, many hundreds of events with energies above 10^{19} eV and about 20 events above 10^{20} eV have now been observed by a number of experiments such as AGASA [2–4], Fly's Eye [5], Haverah Park [6], Yakutsk [7], and most recently the High Resolution Fly's Eye [8].

Most unexpected is the significant flux of events observed above $\sim 7 \times 10^{19}$ eV [2] with no sign of the Greisen-Zatsepin-Kuzmin (GZK) cutoff [9]. A cutoff should be present if the ultra-high energy particles are protons, nuclei, or photons from extragalactic sources. Cosmic ray protons of energies above a

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few 10^{19} eV lose energy to photopion production off the cosmic microwave background (CMB) and cannot originate further than about 50 Mpc away from Earth. Nuclei are photodisintegrated on shorter distances due to the infrared background [10] while the radio background constrains photons to originate from even closer systems [11].

In addition to the presence of events past the GZK cutoff, there has been no clear counterparts identified in the arrival direction of the highest energy events. If these events are protons, cosmic ray observations should finally become astronomy! At these high energies the Galactic and extragalactic magnetic fields do not affect their orbits significantly so that they should point back to their sources within a few degrees. Protons at 10^{20} eV propagate mainly in straight lines as they traverse the Galaxy since their gyroradii are $\sim$ 100 kpc in μG fields which is typical in the Galactic disk. Extragalactic fields are expected to be $\ll \mu$G [12,13], and induce at most $\sim 1^o$ deviation from the source. Even if the Local Supercluster has relatively strong fields, the highest energy events may deviate at most $\sim 10^o$ [14,15]. At present, no correlations between arrival directions and plausible optical counterparts such as sources in the Galactic plane, the Local Group, or the Local Supercluster have been clearly identified. Ultra high energy cosmic ray (UHECR) data are consistent with an isotropic distribution of sources in sharp contrast to the anisotropic distribution of light within 50 Mpc from Earth.

The absence of a GZK cutoff and the isotropy of arrival directions are two of the many challenges that models for the origin of UHECRs face. This is an exciting open field, with many scenarios being proposed but no clear front runner. Not only the origin of these particles may be due to physics beyond the standard model of particle physics, but their existence can be used to constrain extensions of the standard model such as violations of Lorentz invariance (see, e.g., [16]).

In the next section, a brief summary of the challenges faced by all theoretical models is given. In §3, astrophysical accelerators or "bottom-up" scenarios are reviewed, hybrid models are discussed in §4, and top-down scenarios in §5. To conclude, future observational tests of UHECR models and their implications are discussed in §6. For previous reviews of UHECR models, the reader is encouraged to consult [17–22].

2 The Challenge

In attempting to explain the origin of UHECRs, models confront a number of challenges. The extreme energy is the greatest challenge that models of astrophysical acceleration face while for top-down models the observed flux represents the highest hurdle. To complete the puzzle, models have to match the spectral shape, the primary composition, and the arrival direction distribution of the observed events.

2.1 Energy

The observed highest energy event at 3.2×10^{20} eV [5] argues for the existence of Zevatrons in nature [20], accelerators that reach as high as one ZeV (ZeV=10^{21} eV) which is a billion times the energy limit of current terrestrial accelerators. The energetic requirements at the source may be even more stringent if the distance traveled by the UHE primaries from source to Earth is larger than typical interaction lengths. As can be seen from Figure 1 of [1] (from [23]), if 3×10^{20} eV is taken as a typical energy for protons travelling in straight lines, accelerators located further than 30 Mpc need to reach above 1 ZeV while those located further than 60 Mpc require over 10 ZeV energies. Depending on the strength and structure of the magnetic field along the primary's path, the distance traveled can be significantly larger than the distance to the source. As magnetic fields above $\sim 10^{-8}$ G may thread extragalactic space [14,13,24], protons travel in curved paths and sources need to be either more energetic or located closer to Earth [25,26,15].

There are great difficulties with finding plausible accelerators for such extremely energetic particles [20]. As discussed in §3, even the most powerful astrophysical objects such as radio galaxies and active galactic nuclei can barely accelerate charged particles to energies as high as 10^{20} eV. If the origin of these events date back to the early universe, then the energy is not as challenging since typical symmetry breaking scales that give rise to early universe relics can be well above the ZeV scale (§5).

2.2 Flux

At 10^{20} eV, the observed flux of UHECRs is about ~ 1 event/km^2/century which has strongly limited our ability to gather more than 20 events after decades of observations [1]. Although challenging to observers, the flux is not particularly constraining in terms of general requirements on astrophysical sources. In fact, this flux equals the flux of gamma-rays in *one* gamma-ray burst that may have taken place in a 50 Mpc radius volume around us [27,28]. In terms of an average energy density, UHECRs correspond to $\sim 10^{-21}$ erg/cm^3, about 8 orders of magnitude less than the cosmic background radiation.

Although less constraining to astrophysical accelerators, flux requirements are very challenging for top-down scenarios. The dynamics of topological defect generation and evolution generally selects the present horizon scale as the typical distance between defects which implies a very low flux. Some scenarios such as monopolia, cosmic necklaces, and vortons have additional scales and may avoid this problem. The possibility of a long lived relic particle that cluster as dark matter can also more easily meet the flux requirements than general top-down models (§5).

2.3 Spectrum

The energy spectrum of cosmic rays below the expected GZK cutoff (i.e., between $\sim 10^8$ eV and $\lesssim 10^{19}$ eV) is well established to have a steep energy dependence: $N(E) \propto E^{-\gamma}$, with $\gamma \approx 2.7$ up to the "knee" at $E \simeq 10^{15}$ eV and $\gamma \approx 3.1$, for 10^{15} eV $\lesssim E \lesssim 10^{19}$ eV. Cosmic rays of energy below the knee are widely accepted to originate in shocks associated with galactic supernova remnants (see, e.g., [29]), but this mechanism has difficulties producing particles of higher energies [30]. Larger shocks, such as those associated with galactic winds, could reach energies close to the knee [31] and supernova explosions into stellar winds may explain cosmic rays beyond the knee [32]. Although the source of cosmic rays above the knee is not clear, the steepening of the spectrum argues for a similar origin with an increase in losses or decrease in confinement time above the knee. However, the events with energy above $10^{19.5}$ eV show a much flatter spectrum with $1 \lesssim \gamma \lesssim 2$. The drastic change in slope suggests the emergence of a *new component* of cosmic rays at ultra-high energies. This new component is generally thought to be extragalactic [29,5], although, depending on its composition, it may also originate in the Galaxy [33,34], in an extended halo [28], or in the dark matter halo [35]. Galactic and halo origins for UHECRs ease the difficulties with the lack of a GZK cutoff but represent an even greater challenge to acceleration mechanisms.

2.4 Propagation - Losses and Magnetic Fields

In order to contrast plausible candidates for UHECR sources with the observed spectrum and arrival direction distribution, the propagation from source to Earth needs to be taken into account. Propagation studies involve both the study of losses along the primaries' path as well as the structure and magnitude of cosmic magnetic fields that determine the trajectories of charged primaries and influence the development of the electromagnetic cascade (see, e.g., [36]).

For primary protons the main loss processes are pair production [37] and photopion production off the CMB that gives rise to the GZK cutoff [9]. For straight line propagation, loss processes limit sources of 10^{20} eV to be within ~ 50 Mpc from us and a clear cutoff should be present at $\sim 7 \times 10^{19}$ eV. Even with the small number of accumulated events at the highest energies, the AGASA spectrum seems incompatible with a GZK cutoff for a homogeneous extragalactic source distribution [2]. The shape of the cutoff can be modified if the distribution of sources is not homogeneous [38,39] and if the particle trajectories are not rectilinear (e.g., the case of sizeable intergalactic magnetic fields) [25,40–42,26,15]. In fact, if the observed distribution of galaxies in the local universe is used to simulate the range of possible cutoff shapes, the AGASA spectrum is still consistent with sources distributed with the luminous matter given the poor statistics [39]. The need for a new component should become apparent with the increased statistics of future observatories [1].

Charged particles of energies up to 10^{20} eV can be deflected significantly in cosmic magnetic fields. In a constant magnetic field of strength $B = B_6 \mu$G, particles of energy $E = E_{20} 10^{20}$eV and charge Ze have Larmor radii of $r_L \simeq 110$ kpc $(E_{20}/B_6 Z)$. If the UHECR primaries are protons, only large scale intergalactic magnetic fields affect their propagation significantly [25,40–42,26,15] unless the Galactic halo has extended fields [40]. For higher Z, the Galactic magnetic field can strongly affect the trajectories of primaries [33,43].

Whereas Galactic magnetic fields are reasonably well studied, extragalactic fields are still very ill understood [12]. Faraday rotation measures indicate large magnitude fields ($\sim \mu$G) in the central regions of clusters of galaxies. In regions between clusters, the presence of magnetic fields is evidenced by synchrotron emission but the strength and structure are yet to be determined. On the largest scales, limits can be imposed by the observed isotropy of the CMB and by a statistical interpretation of Faraday rotation measures of light from distant quasars. The isotropy of the CMB can constrain the present horizon scale fields $B_{H_0^{-1}} \lesssim 3 \times 10^{-9}$ G [44]. Although the distribution of Faraday rotation measures have large non-gaussian tails, a reasonable limit can be derived using the median of the distribution in an inhomogeneous universe: for fields assumed to be constant on the present horizon scale, $B_{H_0^{-1}} \lesssim 10^{-9}$ G; for fields with 50 Mpc coherence length, $B_{50\mathrm{Mpc}} \lesssim 6 \times 10^{-9}$ G; while for 1 Mpc coherence length, $B_{Mpc} \lesssim 10^{-8}$ G [13]. These limits apply to a $\Omega_b h^2 = 0.02$ universe and use quasars up to redshift $z = 2.5$. Local structures can have fields above these upper limits as long as they are not common along random lines of site between $z = 0$ and 2.5 [14,13,24].

Of particular interest is the field in the local 10 to 20 Mpc volume around us. If the Local Supercluster has fields of about 10^{-8} G or larger, the propagation of ultra high energy protons becomes diffusive and the spectrum and angular distribution at the highest energies are significantly modified [45,14,26]. As shown in Figure 1 (from [26]), a source with spectral index $\gamma \gtrsim 2$ that can reach $E_{max} \gtrsim 10^{20}$ eV is constrained by the overproduction of lower energy events around 1 to 10 EeV (EeV $\equiv 10^{18}$ eV). Furthermore, the structure and magnitude of magnetic fields in the Galactic halo [40,43] or in a possible Galactic wind can also affect the observed UHECRs. In particular, if our Galaxy has a strong magnetized wind, what appears to be an isotropic distribution in arrival directions may have originated on a small region of the sky such as the Virgo cluster [46]. In the future, as sources of UHECRs are identified, large scale magnetic fields will be better constrained [47].

Fig. 1. Flux vs. Energy with $E_{max} = 10^{21}$ eV at source. Choices of source distance r(Mpc), spectral index γ, proton luminosity L_p(erg/s), and LSC field B(μG) are: solid line (13 Mpc, 2.1, 2.2×10^{43} erg/s, 0.05 μG); dotted line (10 Mpc, 2.1, 10^{43} erg/s, 0.1 μG); dashed line (10 Mpc, 2.4, 3.2 $\times 10^{43}$ erg/s, 0.1 μG); and dashed-dotted line (17 Mpc, 2.1, 3.3×10^{43} erg/s, 0.05 μG). Data points from [4,5].

If cosmic rays are heavier nuclei, the attenuation length is shorter than that for protons due to photodisintegration on the infrared background [10]. However, UHE nuclei may be of Galactic origin. For large enough charge, the trajectories of UHE nuclei are significantly affected by the Galactic magnetic field [43] such that a Galactic origin can appear isotropic [33]. The magnetically induced distortion of the flux map of UHE events can give rise to some higher flux regions where caustics form and some much lower flux regions (blind spots) even for an originally isotropic distribution of sources [43]. Such propagation effects are one of the reasons why full-sky coverage is necessary for resolving the UHECR puzzle.

The trajectories of neutral primaries are not affected by magnetic fields. If associated with luminous systems, sources of UHE neutral primaries should point back to their nearby sources. The lack of counterpart identifications suggests that if the primaries are neutral, their origin involves physics beyond the standard model (§4 & §5).

2.5 Cosmography

The distribution of arrival directions of UHECRs can in principle hold the key to solving the UHECR puzzle. Within a 50 Mpc radius volume around us, the most well-known luminous structures are the Galactic plane, the Local Group and the large-scale galaxy distribution with a relative overdensity around the Local Supercluster. The Galactic halo is another noteworthy structure that is expected to be a spheroidal overdensity of dark matter centered at the Galactic disk while the dark matter distribution on larger scales correlates with the luminous matter distribution. For the few highest energy events, there is presently no strong evidence of correlations between the events' arrival direction and any of the known nearby luminous structures: the distribution is consistent with isotropy [3,48]. For slightly lower energies, some correlations may have been detected. For events around 40 EeV, a positive correlation with the Supergalactic plane is found but only at the 1 σ level [49]. For even lower energies, a more significant correlation was recently announced by AGASA: the arrival direction distribution of EeV events shows a correlation with the Galactic center and the nearby Galactic spiral arms [50]. If confirmed, this correlation would be strong evidence for a Galactic origin of EeV cosmic rays.

2.6 Composition

An excellent discriminator between proposed models is the composition of the primaries. In general, Galactic disk models have to invoke heavier nuclei such as iron to be consistent with the isotropic distribution, while extragalactic astrophysical models tend to favor proton primaries. Photon primaries are more common among top-down scenarios although nucleons can reach comparable fluxes for some models [22]. Experimentally, the composition can be determined by the muon content of the shower in ground arrays and the depth of shower maximum in fluorescence detectors [1]. Unfortunately, the muon content analysis is not very effective at the highest energies. Data from the largest air shower array, AGASA, disfavor photon primaries and indicate a fixed composition across the EeV to 100 EeV range but does not distinguish nuclei from proton primaries [51]. The shower development of the highest energy event ever detected, the 320 EeV Fly's Eye event, is consistent with either proton or iron [5] and also disfavors a photon primary [52]. This event constrains hypothetical hadronic primaries to have masses below $\sim$ 50 GeV [53]. Since fluctuations in shower development are usually large, strong composition constraints await larger statistics of future experiments.

2.7 Clusters of Events

A final challenge for models of UHECRs is the possible small scale clustering of arrival directions [54,3,49]. AGASA reported that their 47 events above 40 EeV show three double coincidences (doublets) and one triple coincidence (triplet) in arrival directions, a $\lesssim$1% chance probability [3]. Adding to the AGASA data that of Haverah Park, Volcano Ranch, and Yakutsk, the 51 events above 50 EeV show one doublet and two triplets [49]. Although these could be due to a statistical fluctuation since the chance probability for the combined set is $\sim$ 10% [49], they may indicate the position of the sources. (When limited to $\pm 10^o$ around the Supergalactic plane the chance probability decreases to $\sim$ 1%.) If these clusters indicate the position of sources, the

Fig. 2. B vs. L, for $E_{max} = 10^{20}$ eV, $Z = 1$ (dashed line) and $Z = 26$ (solid line).

arrival times and energies of some of the events are inconsistent with a burst and require long lived sources. Furthermore, if the clustering is confirmed by larger data sets and their distribution correlates with some known matter distributions in the nearby universe, the composition of the primaries [55] as well as the magnitude of extragalactic magnetic fields would be strongly constrained [47,42]. Alternative explanations for the clustering involve either the effect of caustics in the propagation due to magnetic fields [43] or the clustering of dark matter in the halo of the Galaxy.

3 Facing the Challenge with Zevatrons

The challenge put forth by these observations has generated two different approaches to reaching a solution: a 'bottom-up' and a 'top-down'. A bottom-up approach involves looking for *Zevatrons* [20], possible acceleration sites in known astrophysical objects that can reach ZeV energies, while a top-down approach involves the decay of very high mass relics from the early universe and physics beyond the standard model of particle physics. Bottom-up models are discussed first and top-down models in the next section.

Acceleration of UHECRs in astrophysical plasmas occurs when large-scale macroscopic motion, such as shocks and turbulent flows, is transferred to individual particles. The maximum energy of accelerated particles, $E_{\rm max}$, can be estimated by requiring that the gyroradius of the particle be contained in the acceleration region. Therefore, for a given strength, B, and coherence length, L, of the magnetic field embedded in an astrophysical plasma, $E_{\rm max} = Ze\,B\,L$, where Ze is the charge of the particle. The "Hillas plot" [17] in Figure 2 shows that, for $E_{max} \gtrsim 10^{20}$ eV and $Z \sim 1$, the only known astrophysical sources with reasonable BL products are neutron stars ($B \sim 10^{13}$ G, $L \sim 10$ km), active galactic nuclei (AGNs) ($B \sim 10^4$ G, $L \sim 10$ AU), radio lobes of AGNs ($B \sim 0.1\mu$G, $L \sim 10$ kpc), and clusters of galaxies ($B \sim \mu$G, $L \sim 100$ kpc).

In general, when these sites are considered more carefully, one finds great difficulties due to either energy losses in the acceleration region or the great distances of known sources from our Galaxy [56]. In many of these objects shock acceleration is invoked as the primary acceleration mechanism. Although effective in the acceleration of lower energy cosmic rays, shock acceleration is unable to reach ZeV energies for most plausible acceleration sites [30] with the possible exception of shocks in radio lobes. Unipolar inductors are often invoked as plausible alternative to shocks [18,20].

3.1 Cluster Shocks

Moving from right to left on Figure 2, cluster shocks are reasonable sites to consider for UHECR acceleration, since E_{max} particles can be contained by cluster fields. However, the propagation of these high energy particles inside the cluster medium is such that they do not escape without significant energy losses. In fact, efficient losses occur on the scales of clusters of galaxies for the same reason that a GZK cutoff is expected, namely, the photopion production off the CMB. Losses limit UHECRs in cluster shocks to reach at most ~ 10 EeV [57].

3.2 AGN - Jets and Radio Lobes

Extremely powerful radio galaxies are likely astrophysical UHECR accelerators [17,58] (for a recent review see [59]). Jets from the central black-hole of the active galaxy end at a termination shock where the interaction of the jet with the intergalactic medium forms radio lobes and 'hot spots'. Of special interest are the most powerful AGNs such as Fanaroff-Riley class II objects [60]. Particles accelerated in hot spots of FR-II sources via first-order Fermi acceleration may reach energies well above an EeV and may explain the spectrum up to the GZK cutoff [61]. A nearby specially powerful source may be able to reach energies past the cutoff [61]. Alternatively, the crossing of the tangential discontinuity between the relativistic jet and the surrounding medium may also be able to make protons reach the necessary energies [62]. The spectrum of UHECR primaries formed by the latter proposal is flatter than the Fermi acceleration at the hot spots scenario. Improved statistics of events past the GZK cutoff by future experiments should better determine the spectral index, and therefore, discriminate between plausible sites for UHECR acceleration in radio sources.

Both hot spots and tangential jet discontinuity models avoid the efficient loss processes faced by acceleration models in AGN central regions (§3.3). However, the location of possible sources is problematic for both types of mechanisms. Extremely powerful AGNs with radio lobes and hot spots are rare and far apart. The closest known object is M87 in the Virgo cluster ($\sim$ 18 Mpc away) and could be a main source of UHECRs. Although a single nearby source may be able to fit the spectrum for a given strength and structure of the intergalactic magnetic field [26], it is unlikely to match the observed arrival direction distribution. After M87, the next known nearby source is NGC315 which is already too far at a distance of $\sim$ 80 Mpc.

A recent proposal gets around this challenge by invoking a Galactic wind with a strongly magnetized azimuthal component [46]. Such a wind can significantly alter the paths of UHECRs such that all the observed arrival directions of events above 10^{20} eV trace back to the Virgo cluster close to M87 [46]. If our Galaxy has a wind with the required characteristics to allow for this magnetic focusing is yet to be determined. Future observations of UHECRs from the Southern Hemisphere (e.g., the Southern Auger Site [23]) will provide data on previously unobserved parts of the sky and help distinguish plausible proposals for the effect of local magnetic fields on arrival directions. Once again full sky coverage is a key discriminator of such proposals.

3.3 AGN - Central Regions

The powerful engines that give rise to the observed jets and radio lobes are located in the central regions of active galaxies and are powered by the accretion of matter onto supermassive black holes. It is reasonable to consider the central engines themselves as the likely accelerators [17,63,18]. In principle, the nuclei of generic active galaxies (not only the ones with hot spots) can accelerate particles via a unipolar inductor [63] not unlike the one operating in pulsars [64]. In the case of AGNs, the magnetic field is provided by the infalling matter and the spinning black hole horizon provides the imperfect conductor for the unipolar induction. Close to the horizon of a black hole ($R \simeq GM/c^2$) with a mass $\mathrm{M} = 10^9 M_9\ \mathrm{M}_\odot$, the electromotive force is [65,63]: $emf \propto cBR \approx 4.4 \times 10^{20} B_4 M_9$Volts for a magnetic field $B = 10^4 B_4$ G. It is reasonable to expect that such fields are reached in some nearby AGNs. In addition, the arrival direction of events above 5×10^{19} eV correlate qualitatively well with active galaxies within 100 Mpc [66]. Although it is not clear how statistically significant the correlation is, the clustering of UHECR events in the same regions of the sky where clusters of AGNs reside is certainly tantalizing.

The problem with AGNs as UHECR sources is two-fold: first, UHE particles face debilitating losses in the acceleration region due to the intense radiation field present in AGNs, and second, the spatial distribution of objects should give rise to a GZK cutoff of the observed spectrum. In the central regions of

AGNs, loss processes are expected to downgrade particle energies well below the maximum achievable energy. This limitation has led to the proposal that quasar remnants, supermassive black holes in centers of inactive galaxies, are more effective UHECR accelerators [67]. In this case, losses are not as significant. In addition, the problem with the rarity of very luminous radio sources (§3.2) is also avoided since any galaxy with a supermassive quiescent black hole could host a UHECR accelerator.

Quasar remnants are manifestly underluminous such that losses in the acceleration region are kept at a reasonably low level [67]. Although presently underluminous, the underlying supermassime black holes are likely to be sufficiently spun-up for individual particles to be accelerated. An incomplete sample of 32 massive dark objects (MDOs) in the nearby universe (of which 8 are within 50 Mpc) [68] finds about 14 MDOs which could have fields strong enough for an $emf \gtrsim 10^{20}$ Volts [67]. From the number density and accretion evolution of quasars, more than 40 quasar remnants are expected to have $\gtrsim 4 \times 10^{8}$ $M_\odot$ within a 50 Mpc volume while more than a dozen would have $\gtrsim 10^{9}$ $M_\odot$ [69].

The second difficulty with AGNs mentioned above, namely the spatial distribution and the GZK cutoff induced by the more distance galaxies, is not avoided by the quasar remnants proposal unless the spectrum is fairly hard. However, it is still within the errors of the current UHECR spectrum the possibility that a GZK cutoff is presently hidden due to the effect of the local clustering of galaxies [39]. This ambiguity should be lifted and a GZK cutoff made apparent by future experiments.

3.4 Neutron Stars

From Figure 2, the last astrophysical objects capable of accelerating UHECRs are neutron stars (see, e.g., [17,18]). With the recent identification of "magnetars" [70] (neutron stars with fields of $\gtrsim 10^{14}$ G) as the sources of soft gamma ray repeaters [71], neutron stars have strong enough fields to reach past the required E_{max} as in Figure 2. Acceleration processes inside the neutron star light cylinder are bound to fail much like the AGN central region case: ambient magnetic and radiation fields induce significant losses [72]. However, the plasma that expands beyond the light cylinder is freer from the main loss processes and may be accelerated to ultra high energies. One possible solution to the UHECR puzzle is the proposal that the early evolution of neutron stars may be responsible for the flux of cosmic rays beyond the GZK cutoff [73,34,74]. In this case, UHECRs originate mostly in the Galaxy and the arrival directions require that the primaries have large Z (i.e., primaries are heavier nuclei).

Newly formed, rapidly rotating neutron stars may accelerate iron nuclei to UHEs through relativistic MHD winds beyond their light cylinders [34,74].

The nature of the relativistic wind is not yet clear, but observations of the Crab Nebula indicate that most of the rotational energy emitted by the pulsar is converted into the flow kinetic energy of the particles in the wind (see, e.g., [75]). Recent observations of the Crab Nebula by the Chandra satellite indicate both a complex disk and jet structure that is probably associated with the magnetic wind as well as the presence of iron in the expanding shell. Understanding the structure of observable pulsar winds such as the Crab nebula will help determine if during their first years pulsars were efficient Zevatrons.

If most of the magnetic energy in the wind zone is converted into particle kinetic energy and the rest mass density of the wind is not dominated by electron-positron pairs, particles in the wind can reach a maximum energy of $E_{max} \simeq 8 \times 10^{20}\, Z_{26} B_{13} \Omega_{3k}^2\,$eV, for iron nuclei ($Z_{26} \equiv Z/26 = 1$), neutron star surface fields $B = 10^{13} B_{13}$ G, and initial rotation frequency $\Omega = 3000\Omega_{3k}$ s^{-1}. In the rest frame of the wind, the plasma is relatively cold while in the star's rest frame the plasma moves with Lorentz factors $\gamma \sim 10^9 - 10^{10}$.

Iron nuclei can escape the remnant of the supernova without suffering significant spallation about a year after the explosion. As the ejected envelope of the pre-supernova star expands, the young neutron star spins down and E_{max} decreases. Thus, a requirement for relativistic winds to supply UHECRs is that the column density of the envelope becomes transparent to UHECR iron before the spin rate of the neutron star decreases significantly. The allowed parameter space for this model is shown in Figure 3. Magnetars with the largest surface fields spin down too quickly for iron nuclei to escape unless the remnant is asymmetric with lower density "holes." The spectrum of UHECRs accelerated by young neutron star winds is determined by the evolution of the rotational frequency which gives $\gamma \simeq 1$, at the hard end of the allowed γ range (§2.3).

Depending on the structure of Galactic magnetic fields, the trajectories of iron nuclei from Galactic neutron stars may be consistent with the observed arrival directions of the highest energy events [33]. Moreover, if cosmic rays of a few times 10^{18} eV are protons of Galactic origin, the isotropic distribution observed at these energies is indicative of the diffusive effect of the Galactic magnetic fields on iron at $\sim 10^{20}$ eV.

Another recent proposal involving neutron stars suggests that relativistic winds formed around neutron star binaries may generate high energy cosmic rays in a single shot , ^{2} acceleration [76], where , is the bulk Lorentz factor. However, the , ^{2} acceleration process is likely to be very inefficient which renders the proposal insufficient for explaining UHECRs [77].

In general, there is an added bonus to considering the existence of Zevatrons in Galactic systems: one may find Pevatrons or Evatrons instead. These may

Fig. 3. Allowed regions of Ω vs. B for $E_{cr} = 10^{20}$ eV (solid line) and 3×10^{20} eV (dashed lines) with envelope masses $M_{env} = 50 M_{\odot}$ and $5 M_{\odot}$. Horizontal line indicates the minimum period for neutron stars ~ 0.3 ms.

explain the origin of cosmic rays from the knee at 10^{15} eV up to the "ankle" at 10^{18} eV that remain largely unidentified.

3.5 Gamma-Ray Bursts

Before moving on to more exotic explanations for the origin of UHECRs, one should consider astrophysical phenomena that may act as Zevatrons not included in Figure 2. In effect, transient high energy phenomena such as gamma-ray bursts (bursts of $\sim 0.1 - 1$ MeV photons that last up to a few seconds) may accelerate protons to ultra-high energies [27,28]. The systems that generate gamma-ray bursts (GRBs) remain unknown but evidence that GRBs are of cosmological origin and involve a relativistic fireball has been mounting with the recent discovery of X-ray, optical, and radio afterglows [78] and the subsequent identification of host galaxies and their redshifts.

Aside from both having unknown origins, GRBs and UHECRs have some similarities that argue for a common origin. Like UHECRs, GRBs are distributed isotropically in the sky [79], and the average rate of γ-ray energy emitted by GRBs is comparable to the energy generation rate of UHECRs of energy $> 10^{19}$ eV in a redshift independent cosmological distribution of sources [27], both have $\approx 10^{44}$erg Mpc^{-3}yr^{-1}.

Although the systems that generate GRBs have not been identified, they are likely to involve a relativistic fireball (see, e.g., [80]). Cosmological fireballs may generate UHECRs through Fermi acceleration by internal shocks [27,28]. In this model the generation spectrum is estimated to be $dN/dE \propto E^{-2}$ which is consistent with observations provided the efficiency with which the wind kinetic energy is converted to γ-rays is similar to the efficiency with which it is converted to UHECRs [27]. Acceleration to $> 10^{20}$ eV is possible provided that , of the fireball shocks are large enough and that the magnetic field is close to equipartition.

There are a few problems with the GRB–UHECR common origin proposal. First, events past the GZK cutoff require that only GRBs from $\lesssim$50 Mpc contribute. However, only *one* burst is expected to have occurred within this region over a period of 100 yr. Therefore, a very large dispersion of $\gtrsim$ 100 yr in the arrival time of protons produced in a single burst is a necessary condition. The deflection by random magnetic fields combined with the energy spread of the particles is usually invoked to reach the required dispersion [27,25]. If the dispersion in time is achieved, the energy spectrum for the nearby source(s) is expected to be very narrowly peaked $\Delta E/E \sim 1$ [27,25,47]. Second, the fireball shocks may not be able to reach the required , factors for UHECR shock acceleration [76]. Third, UHE protons are likely to loose most of their energy as they expand adiabatically with the fireball [81]. However, if acceleration happens by internal shocks in regions where the expansion becomes self-similar, protons may escape without significant losses [82]. Fourth, the observed arrival times of different energy events in some of the UHE clusters argues for long lived sources not bursts (§2.7). These clusters can still be due to fluctuations but should become clear in future experiments [42]. Finally, the present flux of UHE protons from GRBs is reduced to $\lesssim 10^{42}$erg Mpc^{-3}yr^{-1}, if a redshift dependent source distribution that fits the GRB data is considered [83] (see also [24,84]).

4 Hybrid Models

The UHECR puzzle has inspired proposals that use Zevatrons to generate UHE particles other than protons, nuclei, and photons. These use physics beyond the standard model in a bottom-up approach, thus, named hybrid models.

The most economical among such proposals involves a familiar extension of the standard model, namely, neutrino masses. The most common solution to the atmospheric or the solar neutrino problems entails neutrino oscillations, and hence, neutrino masses (see, e.g., [85]). Recently, the announcement by SuperKamiokande on atmospheric neutrinos has strengthened the evidence for neutrino oscillations and the possibility that neutrinos have a small mass [86]. If some flavor of neutrinos have masses ~ 1 eV, the relic neutrino background will cluster in halos of galaxies and clusters of galaxies. High energy neutrinos ($\sim 10^{21}$ eV) accelerated in Zevatrons can annihilate on the neutrino background and form UHECRs through the hadronic Z-boson decay [87].

This proposal is aimed at generating UHECRs nearby (in the Galactic halo and Local Group halos) while using Zevatrons that can be much further than the GZK limited volume, since neutrinos do not suffer the GZK losses. It is not clear if the goal is actually achieved since the production in the uniform non-clustered neutrino background may be comparable to the local production depending on the neutrino masses [88]. In addition, the Zevatron needed to accelerate protons above ZeVs that can produce ZeV neutrinos as secondaries is quite spectacular and presently unknown, requiring an energy generation in excess of $\sim 10^{48}$erg Mpc^{-3}yr^{-1} [88].

Another suggestion is that the UHECR primary is a new particle. For instance, a stable or very long lived supersymmetric neutral hadron of a few GeV, named *uhecron*, could explain the UHECR events and evade the present laboratory bounds [89]. (Note that the mass of a hypothetical hadronic UHECR primary can be limited by the shower development of the Fly's Eye highest energy event to be below $\lesssim$50 GeV [53].) Both the long lived new particle and the neutrino Z-pole proposals involve neutral particles which are usually harder to accelerate (they are created as secondaries of even higher energy charged primariess) but can traverse large distances without being affected by the cosmic magnetic fields. Thus, a signature of such hybrid models for future experiments is a clear correlation between the position of powerful Zevatrons in the sky such as distant compact radio quasars and the arrival direction of UHE events [90].

Topological defects have also been suggested as possible UHE primaries [91]. Monopoles of masses between $\sim 10^9 - 10^{10}$ GeV have relic densities below the Parker limit and can be easily accelerated to ultra high energies by the Galactic magnetic field [92]. The main challenges to this proposal are the observed shower development for the Fly's Eye event that seems to be inconsistent with a monopole primary and the arrival directions not showing a preference for the local Galactic magnetic field [93].

Another exotic primary that can use a Zevatron to reach ultra high energies is the vorton. Vortons are small loops of superconducting cosmic string stabilized by the angular momentum of charge carriers [94]. Vortons can be a component of the dark matter in galactic halos and be accelerated in astrophysical Zevatrons [95]. Although not yet clearly demonstrated, the shower development profile is also the likely liability of this model.

5 Top-Down Models

It is possible that none of the astrophysical scenarios are able to meet the challenge posed by the UHECR data as more observations are accumulated. In that case, the alternative is to consider top-down models. For example, if the primaries are not iron, the distribution in the sky remains isotropic with better statistics, and the spectrum does not show a GZK cutoff, UHECRs are likely to be due to the decay of very massive relics from the early universe.

This possibility was the most attractive to my dear colleague and friend, David N. Schramm, to whom this volume is dedicated. After learning with the work of Hill [96] that high energy particles would be produced by the decay of supermassive Grand Unified Theory (GUT) scale particles (named X-particles) in monopole-antimonopole annihilation, Schramm joined Hill in proposing that such processes would be observed as the highest energy cosmic rays [97]. Schramm realized the potential for explaining UHECRs with physics at very high energies well beyond those presently available at terrestrial accelerators. One winter in Aspen, CO, he remarked pointing to the ski lift 'why walk up if we can start at the top'. His enthusiasm for this problem only grew after his pioneering work [98]. In the last conference he attended, an OWL workshop at the University of Maryland [99], he summarized the meeting by reminding us that in this exciting field the most conventional proposal involves supermassive black holes and that the best fit models involve physics at the GUT scale and beyond. In this field our imagination is the limit (as well as the low number of observed events).

The lack of a clear astrophysical solution for the UHECR puzzle has encouraged a number of interesting proposals based on physics beyond the standard model such as monopolia annihilation, the decay of ordinary and superconducting cosmic strings, cosmic necklaces, vortons, and superheavy long-lived relic particles, to name a few. Due to the lack of space and a number of recent thorough reviews, only a brief summary of the general features of these proposals will be given here. The interested reader is encouraged to consult the following reviews by long-time collaborators of David Schramm [21,22] and references therein.

The idea behind top-down models is that relics of the very early universe, topological defects (TDs) or superheavy relic (SHR) particles, produced after or at the end of inflation, can decay today and generate UHECRs. Defects, such as cosmic strings, domain walls, and magnetic monopoles, can be generated through the Kibble mechanism [100] as symmetries are broken with the expansion and cooling of the universe (see, e.g., [101]). Topologically stable defects can survive to the present and decompose into their constituent fields as they collapse, annihilate, or reach critical current in the case of superconducting cosmic strings. The decay products, superheavy gauge and higgs bosons, decay into jets of hadrons, mostly pions. Pions in the jets subsequently decay into γ-rays, electrons, and neutrinos. Only a few percent of the hadrons are expected to be nucleons [96]. Typical features of these scenarios are a predominant release of γ-rays and neutrinos and a QCD fragmentation spectrum which is considerably harder than the case of shock acceleration.

ZeV energies are not a challenge for top-down models since symmetry breaking scales at the end of inflation typically are $\gg 10^{21}$ eV (typical X-particle masses vary between $\sim 10^{22} - 10^{25}$ eV) . Fitting the observed flux of UHECRs is the real challenge since the typical distances between TDs is the Horizon scale, $H_0^{-1} \simeq 3h^{-1}$ Gpc. The low flux hurts proposals based on ordinary and superconducting cosmic strings [21,22]. Monopoles usually suffer the opposite problem, they would in general be too numerous. Inflation succeeds in diluting the number density of monopoles [102] usually making them too rare for UHECR production. To reach the observed UHECR flux, monopole models usually involve some degree of fine tuning. If enough monopoles and antimonopoles survive from the early universe, they can form a bound state, named monopolium, that decay generating UHECRs through monopole-antimonopole annihilation [96,103]. The lifetime of monopolia may be too short for this csenario to succeed unless they are connected by strings [104].

Once two symmetry breaking scales are invoked, a combination of horizon scales gives room to reasonable number densities. This can be arranged for cosmic strings that end in monopoles making a monopole string network or even more clearly for cosmic necklaces [105]. Cosmic necklaces are hybrid defects where each monopole is connected to two strings resembling beads on a cosmic string necklace. Necklace networks may evolve to configurations that can fit the UHECR flux which is ultimately generated by the annihilation of monopoles with antimonopoles trapped in the string [105,106].

In addition to fitting the UHECR flux, topological defect models are constrained by limits on the flux of high energy photons observed by EGRET (10 MeV to 100 GeV). The energy density of lower energy cascade photons generated by UHE photons and electrons off the CMB and radio background is limited to $\lesssim 10^{-6}$ eV/cm^3. Figure 4 shows the predicted flux for necklace models given different radio backgrounds and different masses for the X-particle (from [106]). As can be seen from the Figure, protons dominate the flux at lower energies while photons tend to dominate at higher energies depending on the radio background. If future data can settle the composition of UHECRs from 0.01 to 1 ZeV, these models will be well constrained.

Another interesting possibility is the recent proposal that UHECRs are produced by the decay of unstable superheavy relics that live much longer than the age of the universe [35,107]. SHRs may be produced at the end of infla-

Fig. 4. Proton and γ-ray fluxes from necklaces for $m_X = 10^{14}$ GeV (dashed lines), 10^{15} GeV (dotted lines), and 10^{16} GeV (solid lines) normalized to the observed data. γ-high and γ-low correspond to two extreme cases of γ-ray absorption (see, [106]).

tion by non-thermal effects such as a varying gravitational field, parametric resonances during preheating, instant preheating, or the decay of topological defects (see, e.g., [108]). SHRs have unusually long lifetimes insured by discrete gauge symmetries and a sufficiently small percentage decays today producing UHECRs [35,109]. As in the topological defects case, the decay of these relics also generate jets of hadrons. These particles behave like cold dark matter and could constitute a fair fraction of the halo of our Galaxy. Therefore, their halo decay products would not be limited by the GZK cutoff allowing for a large flux at UHEs. The flux of UHECRs predicted by SHRs clustered in our halo is plotted in Figure 5 (from [106]). It is clear that the spectrum is not power law (unlike the case of shock acceleration) and that photon fluxes dominate.

From Figures 4 and 5 it is clear that future experiments should be able to probe these hypotheses. For instance, in the case of SHR and monopolium decays, the arrival direction distribution should be close to isotropic but show an asymmetry due to the position of the Earth in the Galactic Halo [106,110]. Studying plausible halo models and the expected asymmetry will help constrain halo distributions especially when larger data sets are available from future experiments. High energy gamma ray experiments such as GLAST will also help constrain the SHR models due to the products of the electromagnetic cascade [111].

Fig. 5. SHRs or monopolia decay fluxes (for $m_X = 10^{14}\ GeV$): nucleons from the halo (*protons*), γ-rays from the halo (*gammas*) and extragalactic protons. Solid, dotted and dashed curves correspond to different model parameters (see [106]).

6 Conclusion

Next generation experiments such as the High Resolution Fly's Eye [112] which recently started operating, the Pierre Auger Project [23] which is now under construction, the proposed Telescope Array [113], and the OWL-Airwatch satellite [114] will significantly improve the data at the extremely-high end of the cosmic ray spectrum [1]. With these observatories a clear determination of the spectrum and spatial distribution of UHECR sources is within reach. The lack of a GZK cutoff should become apparent with Auger [39] and most extragalactic Zevatrons may be ruled out. The observed spectrum will distinguish Zevatrons from top-down models by testing power laws versus QCD fragmentation fits. The cosmography of sources should also become clear and able to discriminate between plausible populations for UHECR sources. The correlation of arrival directions for events with energies above 10^{20} eV with some known structure such as the Galaxy, the Galactic halo, the Local Group or the Local Supercluster would be key in differentiating between different models. For instance, a correlation with the Galactic center and disk should become apparent at extremely high energies for the case of young neutron star winds [48], while a correlation with the large scale galaxy distribution should become clear for the case of quasar remnants. If SHRs or monopolia are responsible for UHECR production, the arrival directions should correlate with the dark matter distribution and show the halo asymmetry. For these signatures to be tested, full sky coverage is essential. Finally, an excellent discriminator would be an unambiguous composition determination of the primaries. In general, Galactic disk models invoke iron nuclei to be consistent with the isotropic distribution, extragalactic Zevatrons tend to favor proton primaries, while photon primaries are more common for early universe relics. The hybrid detector of the Auger Project should help determine the composition by measuring simultaneously the depth of shower maximum and the muon content of the same shower.

In addition to explaining the origin of UHECRs, GUT to Planck scale physics can potentially be probed by the existence of UHECRs. For instance, the breaking of Lorentz invariance can change the threshold for photopion production significantly in such a way as to be constrained by a clear observation of the GZK cutoff [16]. There are great gains to be made if the data at the highest energies is improved by a few orders of magnitude. The prospect of testing extremely high energy physics as well as solving the UHECR puzzle given all the presently proposed models sends a strong message that the challenge is back in the observational arena. Fortunately, observers have accepted the challenge and are building and planning experiments large enough to resolve these open questions [1].

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References

[1] A. A. Watson, accompaning paper in this volume (1999).

[2] M. Takeda et al., Phys. Rev. Lett. 81 (1998) 1163.

[3] M. Takeda et al. preprint astro-ph/9902239 (submitted to Astrophys. J.).

[4] N. Hayashida Phys. Rev. Lett. 73 (1994) 3491.

[5] D. J. Bird et al. Astrophys J. 441 (1995) 144; Phys. Rev. Lett. 71 (1993) 3401; Astrophys. J. 424 (1994) 491.

[6] M. A. Lawrence, R. J. O. Reid and A. A. Watson, J. Phys. G. Nucl. Part. Phys. 17 (1991) 773.

[7] N. N. Efimov et al., Ref. Proc. International Symposium on *Astrophysical Aspects of the Most Energetic Cosmic Rays*, eds. M. Nagano and F. Takahara (World Scientific, Singapore, 1991), p. 20;

[8] D. Kieda et al., HiRes Collaboration, Proceeds. 26th ICRC Salt Lake (1999).

[9] K. Greisen, Phys. Rev. Lett. 16 (1966) 748; G. T. Zatsepin and V. A. Kuzmin, Sov. Phys. JETP Lett. 4 (1966) 78.

[10] J. L. Puget, F. W. Stecker, and J. H. Bredekamp, Astrophys. J. 205 (1976) 638; F. W. Stecker and M. H. Salamon, Astrophys. J. 512 (1999) 521.

[11] V. S. Berezinsky, Yad. Fiz. 11 (1970) 339; R. J. Protheroe and P. L. Biermann, Astropart. Phys. 6 (1996) 45; erratum ibid. 7 (1997) 181.

[12] P. P. Kronberg, Rep. Prog. Phys., 57 (1994) 325; J. P. Vallée, Fundamentals of Cosmic Physics, 19 (1997) 1.

[13] P. Blasi, S. Burles, and A. V. Olinto, Astrophys. J. 512 (1999) L79.

[14] D. Ryu, H. Kang and P. L. Bierman, Astron. Astrophys. 335 (1998) 19.

[15] G. Sigl, M. Lemoine, and P. Biermann, Astropart. Phys. 10 (1999) 141.

[16] L. Gonzalez-Mestres, Nucl. Phys. B (Proc. Suppl.) 48 (1996) 131; S. Coleman and S. L. Glashow, Phys. Rev. D 59 (1999) 116008; H. Sato and T. Tati, Prog. Theor. Phys. 47 (1972) 1788; D. A. Kirzhnits and V. A. Chechin, Sov. J. Nucl. Phys. 15 (1972) 585; R. Aloisio, P. Blasi, P Ghia, and A. Grillo, preprint INFN/AE-99/24.

[17] A. M. Hillas, Ann. Rev. Astron. Astrophys. 22 (1984) 425.

[18] V. S. Berezinsky, S.V. Bulanov, V. A. Dogiel, V. L. Ginzburg, and V. S. Ptuskin, Astrophysics of Cosmic Rays, (Amsterdam: North Holland, 1990).

[19] T. K. Gaisser, *Cosmic Rays and Particle Physics*, Cambridge University Press (Cambridge, England, 1990).

[20] R. D. Blandford, e-print astro-ph/9906026, *Particle Physics and the Universe*, eds. Bergstrom, Carlson and Fransson (Physica Scripta, World Scientific, 1999).

[21] V. S. Berezinsky, Nucl.Phys. (Proc.Suppl.) 70 (1999) 419.

[22] P. Bhattacharjee and G. Sigl, preprint astro-ph/9811011, Phys. Reps. in press.

[23] J. W. Cronin, Nucl. Phys. B. (Proc. Suppl.) 28 (1992) 213.

[24] G. R. Farrar and T. Piran, e-print astro-ph/9906431.

[25] E. Waxman and J. Miralda-Escude, Astrophys. J. 472 (1996) L89.

[26] P. Blasi and A. V. Olinto, 1999, Phys. Rev. D 59, 023001.

[27] E. Waxman, Phys. Rev. Lett. 75 (1995) 386; ibid., Astrophys. J. 452 (1995) L1.

[28] M. Vietri, Astrophys. J. 453 (1995) 883.

[29] W.I. Axford, Astrophys. J. 90 (1994) 937.

[30] C. T. Norman, D.B. Melrose, and A. Achterberg, Astrophys. J. 454 (1995) 60.

[31] J. R. Jokipii and G. Morfill, Astrophys. J. 312 (1987) 170.

[32] T. Stanev, P.L. Biermann, and T.K. Gaisser, Astron. Astrop. 274 (1993) 902.

[33] V. N. Zirakashvili, D. N. Pochepkin, V. S. Ptuskin, and S. I. Rogovaya, Astron. Lett. 24 (1998) 139.

[34] A. V. Olinto, R. I. Epstein, and P. Blasi, Proceedings of 26th ICRC, Salt Lake City, Utah, 4 (1999) 361.

[35] V. Berezinsky, M. Kachelrieß and A. Vilenkin, Phys. Rev. Lett. 79 (1997) 4302.

[36] S. Lee, A. V. Olinto, and G. Sigl, Astrophys. J. 455 (1995) L21; R. J. Protheroe and P. A. Johnson, Astropart. Phys. 4 (1996) 253; erratum, ibid 5 (1996) 215.

[37] G. B. Blumenthal, Phys. Rev. D 1 (1970) 1596.

[38] V. Berezinsky and S. Grigorieva, Astron. Astroph. 199 (1988) 1.

[39] G. A. Medina-Tanco, Proceedings of 26th ICRC, Salt Lake City, Utah, OG 3.2.52 (1999).

[40] T. Stanev, Astrophys. J. 479 (1997) 290.

[41] G. A. Medina Tanco, E. M. de Gouveia Dal Pino, and J. E. Horvath, Astropart. Phys. 6 (1997) 337.

[42] G. Sigl, M. Lemoine, and A. V. Olinto, Phys. Rev. 56 (1997) 4470.

[43] D. Harari, S. Mollerach, and E. Roulet, (1999) astro-ph/9906309

[44] J. D. Barrow, P. G. Ferreira, and J. Silk, Phys. Rev. Lett. 78 (1997) 3610.

[45] J. Wdowczyk and A. W. Wofendale, Nature 281 (1979) 356; M. Giler, J. Wdowczyk, and A. W. Wolfendale, J. Phys. G.: Nucl. Phys. 6 (1980) 1561; V.S. Berezinsky, S.I. Grigorieva, and V.A. Dogiel 1989, Sov. Phys. JETP 69, 453; ibid. Astronomy and Astrophysics 232 (1990) 582.

[46] E. J. Ahn, P.L. Biermann, G. Medina-Tanco, and T. Stanev, 1999, submitted

[47] M. Lemoine, G. Sigl, A. V. Olinto, and D. Schramm, Astropart. Phys. 486 (1997) L115.

[48] T. Stanev and A. M. Hillas, Proc. of 26th ICRC, (Salt Lake City, Utah, 1999).

[49] Y. Uchihori, M. Ngano, M. Takeda, J. Lloyd-Evans, and A.A. Watson, (1999) astro-ph/9908193.

[50] N. Hayashida et al., Proc. of 26th International Cosmic Ray Conference (Salt Lake City) 3 (1999) 256.

[51] S. Yoshida et al., Proc. of 26th International Cosmic Ray Conference (Salt Lake City) 3 (1999) 256

[52] F. Halzen, R. Vazques, T. Stanev and H. S. Vankov, Astropart. Phys. 3 (1995) 151.

[53] I. F. M. Albuquerque, G. R. Farrar, and E. W. Kolb, Phys. Rev. D. 59 (1999) 015021.

[54] N. Hayashida et al., Phys. Rev. Lett 11 (1996) 1000.

[55] J. Cronin, 1996, preprint

[56] G. Sigl, D. N. Schramm, and P. Bhattacharjee, Astropart. Phys. 2 (1994) 401.

[57] H. Kang, D. Ryu, T.W. Jones, Astropart. Phys. 456 (1996) 422; H. Kang, J. P. Rachen, and P. L. Biermann, Mon. Not. R. Astron. Soc., 286 (1997) 257.

[58] P.L. Biermann and P. Strittmatter, Astropart. Phys. 322 (1987) 643.

[59] P. L. Biermann, J. Phys. G: Nucl. Part. Phys. 23 (1997) 1.

[60] B.L. Faranoff and J. M. Riley, Mon. Not. R. Astron. Soc. 167 (1974) 31P.

[61] J. P. Rachen and P. L. Biermann, Astron. Astrophys. 272 (1993) 161.

[62] M. Ostrowski, Astron. Astrophys. (1999), astro-ph/9803299

[63] K.S. Thorne, R.M. Price, and D. MacDonals, 1986 Black Holes: The Membrane Paradigm (New Haven: Yale Press) and references therein.

[64] P. Goldreich and W. H. Julian, Astrophys. J. 157 (1969) 869.

[65] R.D. Blandford, and R. Znajek, Mon. Not. R. Astron. Soc., 179 (1977) 433.

[66] J. Cronin, Inner Space/Outer Space II, The D.N. Schramm Memorial Symposium (1999).

[67] E. Boldt and P. Ghosh, Mon. Not. R. Astron. Soc. (1999) in press.

[68] J. Magorrian et al., Astron. J. 115 (1998) 2528

[69] A. Chokshi, and E.L. Turner, Mon. Not. R. Astron. Soc. 259 (1992) 421.

[70] C. Thompson and R. C. Duncan, Mon. Not. R. Astron. Soc. 275, 255 (1995).

[71] C. Kouveliotou et al., Nature, 393, 235 (1998).

[72] A. Venkatesan, M. C. Miller, and A. V. Olinto, Astrophys. J. 484 (1997) 323.

[73] A. R. Bell, Mon. Not. R. Astron. Soc. 257 (1992) 493.

[74] P. Blasi, R. I. Epstein, and A. V. Olinto, (1999) astro-ph/9912240.

[75] M. C. Begelman, Astrophys. J., 493 (1998) 291.

[76] Y. A. Gallant and A. Achterberg, Mon. Not. R. Astron. Soc. 305 (1999) L6.

[77] J. Bednarz and M. Ostrowski, Mon. Not. R. Astron. Soc. Lett. (1999), astroph/9909430

[78] E. Costa t et al., Nature 387 (1997) 783; T. J. Galama et al., Nature 395 (1998) 670; D. A. Frail et al., Nature 389 (1997) 261.

[79] C. A. Meegan et al., Nature 355 (1992) 143; B. Paczyński, Nature 355 (1992) 521.

[80] P. Mészáros, in Proc. 17th Texas Conf. Relativistic Astrophysics, Annals Ny. Acad. Sci. No. 759 (NY Acad. Sci., NY 1995);

[81] J. P. Rachen, and P. Mészáros, Proc. 4th Huntsville Symposium on Gamma Ray Bursts, AIP Conf. Proc. 428, (1998) 776

[82] E. Waxman, *Particle Physics and the Universe*, eds. Bergstrom, Carlson and Fransson (Physica Scripta, World Scientific, 1999), astr-ph/9911395.

[83] F. W. Stecker, (1999) astro-ph/9911269.

[84] A. Dar, (1999) astro-ph/9901005.

[85] J. N. Bahcall, *Neutrino Astrophysics*, Cambridge University Press (New York,1989).

[86] Y. Totsuka et al, Super-Kamiokande Collaboration, Inner Space/Outer Space II, The D.N. Schramm Memorial Symposium (1999).

[87] D. Fargion, B. Mele, and A. Salis, astro-ph/9710029; T. Weiler, Astropar. Phys. 11 (1999) 303.

[88] E. Waxman, astro-ph/9804023.

[89] G. R. Farrar, 1996, Phys. Rev. Lett. 76, 4111; D. J. Chung, G. R. Farrar, and E. W. Kolb, 1998, Phys. Rev. D 55, 5749.

[90] G. R. Farrar and P. L. Biermann 1998, Phys. Rev. Lett. 81, 3579.

[91] N. A. Porter, Nuovo Cim. 16 (1960) 958.

[92] T. W. Kephart and T. J. Weiler, 1996, Astropart. Phys. 4, 271.

[93] R. Mohapatra and S. Nussinov, Phys. Rev. D 57 (1998) 1940.

[94] R. L. Davis and E. P. S. Shellard, Nucl. Phys. B 323 (1989) 209.

[95] S. Bonazzola and P. Peter, Astropart. Phys. 7 (1997) 161.

[96] C. T. Hill, Nucl. Phys. B 224 (1983) 469.

[97] D. N. Schramm and C.T. Hill, Proc. 18th ICRC (Bangalore, India) 2 (1983) 393; C. T. Hill and D. N. Schramm, Phys. Lett. B 131 (1983) 247.

[98] C. T. Hill and D. N. Schramm, Phys. Rev. D 31 (1985) 564; C. T. Hill, D.N. Schramm, and T.P. Walker, Phys. Rev. D 36 (1987) 1007; F. A. Aharonian, P. Bhattacharjee, and D. N. Schramm, Phys. Rev. D 46 (1992) 4188; P. Bhattacharjee, C. T. Hill, and D. N. Schramm, Phys. Rev. Lett. 69 (1992) 567; G. Sigl, S. Lee, D. N. Schramm, and P. Bhattacharjee, Science 270 (1995) 1977; G. Sigl, K. Jedamzik, D. N. Schramm, and V. Berezinsky, Phys. Rev. D 52 (1995) 6682; G. Sigl, S. Lee, D. N. Schramm, and P. S. Coppi, Phys. Lett. B 392 (1997) 129; G. Sigl, D. N. Schramm, S. Lee, and C. T. Hill, Proc. Natl. Acad. Sci. USA, Vol 94 (1997) 10501.

[99] Proc. of *Workshop on Observing Giant Cosmic Ray Air Showers from* $> 10^{20}\ eV$ *Particles from Space*, eds. J. F. Krizmanic, J. F. Ormes, and R. E. Streitmatter (AIP Conference Proceedings 433, 1997).

[100] T. W. B. Kibble, J. Phys. A 9 (1976) 1387.

[101] E.W. Kolb and M.S. Turner, *The Early Universe* (Addison-Wesley, Redwood City, California, 1990); A. Vilenkin and E.P.S. Shellard, Cosmic Strings and Other Topological Defects, 1994 (Cambridge University Press:Cambridge); M.B. Hindmarsh and T.W.B. Kibble, Rep. Prog. Phys. 55, 478 (1995) R. Brandenberger, Int. J. Mod. Phys. A 9 (1994) 2117; T. W. B. Kibble, Aust. J. Phys. 50 (1997) 697; T. Vachaspati, Contemp. Phys. 39 (1998) 225.

[102] A. Guth, Phys. Rev. D 23 (1981) 347.

[103] P. Bhattacharjee and G. Sigl, Phys. Rev. D 51 (1995) 4079.

[104] J. J. Blanco-Pillado and K. D. Olum, astro-ph/9904315.

[105] V. Berezinsky and A. Vilenkin, Phys. Rev. Lett. 79 (1997) 5202.

[106] V. Berezinsky, P. Blasi, and A. Vilenkin, Phys. Rev. D 58 (1998) 103515-1.

[107] V.A. Kuzmin and V.A. Rubakov, Yadernaya Fisika 61 (1998) 1122

[108] V. Kuzmin and I. Tkachev, hep-ph/9903542

[109] D. J. H. Chung, E. W. Kolb, and A. Riotto, Phys. Rev. D 59 (1999) 023501; Phys. Rev. Lett. 81 (1998) 4048; V. Kuzmin and I. Tkachev, Phys. Rev. D 59 (1999) 123006; JETP. Lett. 68 (1998) 271.

[110] S.L. Dubovsky and P.G. Tinyakov, Pis'ma Zh. Eksp. Teor. Fiz. 68, 99 (1998) [JETP Lett. 68, 107 (1998)]; A. Benson, A. Smialkowski, A. W. Wolfendale, Astrop. Phys. submitted (1999); V. Berezinsky and A. A. Mikhailov, Phys. Lett. B 449 (1999) 237.

[111] P. Blasi, Phys. Rev. D 60 (1999) 023514.

[112] S. C. Corbató et al., Nucl. Phys. B (Proc. Suppl.) 28B (1992) 36.

[113] M. Teshima et al., Nucl. Phys. B (Proc. Suppl.) 28B (1992) 169.

[114] R. E. Streitmatter, Proc. of *Workshop on Observing Giant Cosmic Ray Air Showers from* $> 10^{20}\ eV$ *Particles from Space*, eds. J. F. Krizmanic, J. F. Ormes, and R. E. Streitmatter (AIP Conference Proceedings 433, 1997).